AdriaClim

Climate change information, monitoring and management tools for adaptation strategies in Adriatic coastal areas

Project ID: 10252001

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PP6 – PI RERA S.D.

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Project ID Number: 10252001

Prject Title: Climate change information, monitoring and management tools for adaptation strategies in Adriatic coastal areas

Priority Axis: 2 - Climate change adaptation

Specific objective: 2.1 - Improve the climate change monitoring and planning of adaptation measures tackling specific effects, in the cooperation area

Work Package Number: WP2

Work Package Title: Communication

Activity Number: 2.2.3.

Activity Title: Publications on EU magazine

AdriaClim – Climate change information, monitoring and management tools for adaptation strategies in Adriatic coastal areas

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AdriaClim is the acronym of the research project funded by the Italy-Croatia Interreg Cooperation Programme dedicated to supporting the development of science-based regional and local climate change adaptation plans. AdriaClim addresses climate change threats by developing regional and local adaptation plans based on up-to-date meteorological and oceanographic information acquired through newly implemented observing and modeling systems for the Adriatic Sea.

The project implementation started on January 1, 2020, and lasts 42 months. The total value of the project amounts to 8,823,415.00 euros, 85 percent of which are grants financed from the ERDF as part of the Interreg cross-border cooperation program Italy-Croatia.

The partner consortium consists of 19 partners from Croatia and Italy who worked on climate change adaptation through different activities. Below are highlighted the most significant activities by project partners.

INSTITUTE OF MARINE SCIENCES (CNR-ISMAR):

The main CNR-ISMAR activities within the AdriaClim Project focused on improving, observing, and modeling the Adriatic climate capacity. They improved the monitoring capacity in the Gulf of Trieste and modeling hydrodynamics in the Veneto Pilot by simulating present and future (up to 2050) coastal sea and lagoon conditions. The modeling results were elaborated to obtain a simplified dataset and maps of the possible climate change impact on extreme sea levels and marine heat waves.

CNR-ISMAR coordinated the activities related to the definition and selection of climate indicators to be used for describing the expected vulnerability, hazards, and impacts in the Adriatic region and specifically in the project pilot areas. Climate indicators were also used to provide a list of quality-checked information (observations and model output) available for each of the project's pilot areas.

AGENZIA REGIONALE PER LA PREVENZIONE E PROTEZIONE AMBIENTALE DEL VENETO – ARPAV:

The meteo-climatic observation system on the coast was improved with the installation by ARPA Veneto of 2 new complete weather stations and upgrading 4 existing measurement sites with new types of sensors such as nefo-ipsometers, present weather sensors, and 4-component net radiometers. ISPRA also implemented its observational system on the Veneto coast by installing 3 new meteo-marine stations with wave buoys and atmospheric sensors in the Po River delta area.

In order to provide indicators, anomalies, and climate trends to the Project partners, ARPAV processed data from the last 30 years and EURO-CORDEX projections, creating the Thredds node of the public data server. CNR-ISMAR analyzed sea and lagoon data, calculating trends over the last thirty years and projecting them into the near future, and implemented the SHYFEM model on a domain representing the Lagoon of Venice and part of the Veneto coast considering climatic changes as well as the effects of the MOSE closure.

ZADRA NOVA DEVELOPMENT AGENCY installed an Innovative Aquaweb system that collects moisture from the air and allows irrigation in dry periods when water sources dry up. This system has been installed at University Farm Baštica.

DUBROVNIK NERETVA COUNTY:

The main Dubrovnik Neretva County activities within the Adriaclim project were to raise awareness of the local population and stakeholders about climate change effects within the pilot area. Also, a Study of the Adaptation and Planning of Measures for Mitigating Climate Change Impacts in the Municipality Dubrovačko Primorje (Adaptation plan) was prepared.

Dubrovnik Neretva County equipped public beaches inside the Slano Bay pilot area with urban equipment and decorated green areas with authentic plants.

THE RUĐER BOŠKOVIĆ INSTITUTE (RBI)

The main activities of the RBI - CMR within the AdriaClim project were the implementation of observation campaigns as part of the Adriatic Sea's long-term national monitoring, and the improvement of the monitoring infrastructure for capacity building and preparation of coastal ecosystem observation and adaptation activities for challenges posed by the impacts of climate change. With the comprehensive dataset of oceanographic measurements produced for the

project's pilot area in the northern and eastern Adriatic Sea and the installation of the highly equipped and modern oceanographic buoy, the RBI - CMR has helped establish reliable real-time data collection for climate change research and monitoring. The activities carried out by the RBI - CMR enabled the development of an interdisciplinary and up-to-date observation system for the northern and eastern Adriatic Sea. As part of the project adaptation activities, RBI CMR shared the scientific results with the public, local management, and educational institutions, creating a strong awareness of climate change challenges in the Adriatic coastal ecosystem.

PUBLIC INSTITUTION RERA SD FOR COORDINATION AND DEVELOPMENT OF SPLIT DALMATA COUNTY (RERA)

The main RERA efforts within the AdriaClim Project were dedicated to raising awareness about climate change.

RERA as a regional coordinator of Split-Dalmatia County decided to improve its existing plan in part related to coastal erosion with the goal to protect beaches and undersea, which are one of Croatia's most important natural resources. PI RERA SD worked continuously with numerous experts on the mentioned guidelines to ensure a quality document that contributes to sea and beach protection and promotes it among policy decision stakeholders.

PI RERA SD organized ecological action of undersea cleaning to raise awareness of the wider public of the importance of climate change adaption and installed smart benches with temperature measurement.

THE INSTITUTE FOR OCEANOGRAPHY AND FISHERIES

The Institute of Oceanography and Fisheries (IOF) research activities are related to two pilot sites: Kaštela Bay and the Neretva River estuary. In the Kaštela Bay IOF scientists are devoted to harmful algal blooms and microbial food webs. The improved monitoring is based on monthly measurements and samplings of numerous oceanographic parameters. In the Neretva River estuary, the IOF team is investigating saline seawater intrusions. Salinization has an adverse impact on agriculture, drinking water sources, and estuary ecosystems, and unfortunately, it is expected that the salinization problem will become even more severe in the future under projected climate change with sea level rise and reduced precipitation and freshwater inflow in summer. The Neretva estuary monitoring is based on continuous measurements of temperature, salinity, and dissolved oxygen content in front of Metković, Opuzen, Komin, and Rogotin. In addition, simultaneous measurements are conducted at an automatic meteo-oceanographic station in Metković harbor. A visual presentation of the collected data is available online in real time on the IOF website.

FONDAZIONE CENTRO EURO-MEDITERRANEO SUI CAMBIAMENTI CLIMATICI

Fondazione CMCC role in the AdriaClim project was various and the different activities performed allowed it to achieve the following results:

- installation of a low-cost and adaptable system to equip one of the Torre Guaceto MPA delimitation buoys (Apulia Pilot Site) with oceanographic sensors;
- implementation of subregional modeling in the Adriatic Sea region, incorporating atmospheric (WRF) and oceanic (NEMO) models with resolutions of a few kilometers (6km and 2km, respectively), in addition to a hydrological model (WRF-hydro) with a resolution of hundreds of meters, in order to provide a 30-year period of historical simulations and future projections under the RCP8.5 scenario;
- implementation, test, and run of a wave model based on WW3 forced by 3 different atmospheric datasets to provide wave hindcast and projections in the Adriatic Sea at 2 km resolution;
- computation of a huge set of indicators (for hydrology, atmosphere, sea-state, and biogeochemistry) at Adriatic and pilot scale;
- design, implementation, and deployment of the distributed data repository, based on a federation of ERDDAP data server nodes. When needed, data post-processing is applied to the datasets, before uploading them to the data repository;
- fostering climate literacy in the Adriatic Sea through an innovative, interactive platform (https://www.climateliteracy.eu) in which climate change information, tools, and data are narrated in a multidisciplinary way to help people understand what climate literacy is and what is the meaning of successful adaptation to climate change - and how to practically do it.

ALMA MATER STUDIORUM UNIVERSITA' DI BOLOGNA

UNIBO was responsible for the monitoring of nutrient (C, N, P) concentrations in sediments and seawater conditions on the Emilia-Romagna coast, and to study the potential impacts of climate on the Adriatic coast. In the last two years and with four ocean sampling campaigns, UNIBO team detected the effect of climate changes on the nutrient concentration in the sediments and on seawater column conditions (salinity and temperature) mostly related to drought conditions and, so, the decrease of riverine input. Additionally, UNIBO modeling activity was focused on the biogeochemical modeling of the whole Adriatic basin and on the downscaled simulation of the Emilia-Romagna. The simulations were carried out for the historical period (1992–2020) and for a scenario (2022–2050). Results of models, supported by monitoring data, showed a sensible decrease in the discharge of most of the rivers of the Adriatic Sea with a consequently reduced flux of nutrients and an increase of the salinity, especially in the northern Adriatic Sea. These conditions may threaten the Adriatic Sea in the next future with negative effects on the ecosystems and humans.

ENTE REGIONE MARCHE

A major activity within AdriaClim Project was the Regional Climate Adaptation Plan. The main characteristic of this Plan, and its distinct feature, is the fact that it is based on regional information, analyses, and studies. This allows all sectors in the region to be adapted to climate change in the most appropriate way.

The Plan defines the instruments that can be implemented to guarantee climate change adaptation over the next few years at a general and sectoral level.

AZIENDA ULSS N. 3 SERENISSIMA

Veneto Coastal Pilot - Adaptation, mitigation, and intervention plan was developed by ULSS3 Serenissima which will implement specific functions of the "Medical Board" tool used in AULSS3's territorial health governance.

The development of the 'Medical Board' was aimed at supporting the action of initiative medicine that the AULSS3 intends to extend throughout the territory in favor of the population most exposed to the effects of climate change and of the increasingly intense and frequent 'heat waves'; this action intends to identify social vulnerabilities, meaning people who present precarious health conditions combined with situations of loneliness and indigence.

In addition, an experiment was started on mapping pathologies and analyzing how they change in relation to climatic adverse events. This was done by analyzing the flow of emergency room admissions and ordinary hospitalizations.

REGIONE MOLISE

Molise Region organized online and face-to-face meetings. It implemented a stakeholder mapping so as to identify key stakeholders to be invited to the workshops as part of the participatory process of the project. It created a preliminary report of the Molise coastal pilot site other than dissemination and promotional material, contents and topics to be covered during the workshops. The Region organized a launching event on the 25th of March 2022 and three thematic workshops involving the coastal municipalities and local stakeholders. The results, derived from the workshop analysis plus the legislation and territorial analysis of the Molise pilot area brought to the identification of the 24 most relevant adaptation actions and the elaboration of the Regional guidelines for Climate Change adaptation on the coastal ecosystem as one of the main results of AdriaClim project, that was presented during the Final dissemination event organized in June 2023.

In addition, the Region has installed a weather-marine station at Termoli to monitor sea and weather data along the Molise coast.

REGIONE EMILIA ROMAGNA

Region Emilia-Romagna's main activity within AdriaClim Project was the development of an Adaptation Strategy for the Coast and the coordination of the related pilot activity. The activity was initiated and coordinated by the Regional offices, but an articulated participatory process was designed and implemented during the three years of the project. The process involved many stakeholders from a number of Regional services, municipalities, other territorial bodies, local economic operators, universities and research institutes, environmentalist associations, and youth organizations too, in an intergenerational perspective. The document was then submitted to public consultation to receive more contributions and reviews.

The four pillars of the resulting Strategy are: to free up space along the coast and keep beaches free from structures and infrastructures; ensure the supply of sediments to the coastal system, from internal and external sources; promote the integration of risks and costs into decision-making processes on planning transformations and investments; maintain a Knowledge System updated on coastal and river dynamics.

ARPAE

As Lead Partner, besides the technical and communication activities developed during the project, Arpae organized the administrative aspects. It was the communication channel between the partners and the Joint Secretariat. As for communication activities, Arpae organized an event for policymakers in Brussels and the final conference of the project in Ravenna (Italy).

Furthermore, Arpae acquired a new wave buoy and a GNSS (Global Navigation Satellite System) to improve the observing network along the Emilia-Romagna coast.

It also coordinated the development of the AdriaClim geoportal that makes available data and model results. This is to facilitate and have better-informed decision-making processes for the development of adaptation plans. As a result, Arpae calculated sets of climate indicators based on historical observations to improve the knowledge of the current climatic conditions along its regional coast. Oceanographic and land field campaigns have also been conducted during the project as a means to acquire new data and check the best location for installing new equipment.

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D.2.2.3 Publications

on national magazines

Article in national magazine il Piccolo

Author(s)	Benedetta Moro
PPs	PP11 ARPAFVG
Title	Radar vicino alla Diga contro l’inquinamento
Magazine	IL PICCOLO
Date	28/09/2021

Article in national magazine SNPA

Author(s)	
PPs	PP11 ARPA FVG
Title	I progetti europei per la salvaguardia del mare sono stati il focus del quinto appuntamento con “A misura di mare” di Arpa FVG
Magazine	SNPAMBIENTE
Date	29/09/2021

Radar vicino alla Diga contro l'inquinamento

Il frutto dell'accordo tra la lega navale e l'arpa

BENEDETTA MORO

28 SETTEMBRE 2021

Una doppia firma per la salvaguardia del mare. Ieri, sul Molo Audace, nel quinto appuntamento del ciclo d'incontri organizzato dall'Arpa Fvg in collaborazione con l'Autorità portuale, si sono impegnati in una convenzione la Lega Navale, concessionaria dell'area della Diga vecchia, rappresentata dal presidente Pierpaolo Scubini, e la stessa Arpa Fvg, con il direttore tecnico-scientifico Anna Lutman, per inserire un radar meteo-marino posto proprio vicino alla Diga che permetterà di monitorare le correnti superficiali e l'altezza delle onde. Grazie a questo e altri strumenti, si analizzerà l'evolversi di eventuali sversamenti d'idrocarburi e si contribuirà a ridurre i tempi d'intervento delle autorità, in primis la Capitaneria.

Ma ieri sono stati presentati anche tre dei sei progetti europei aderenti al programma Interreg tra Italia e Croazia avviati nell'Alto Adriatico con il coinvolgimento dell'Arpa Fvg. In totale i finanziamenti corrispondono a 33,2 milioni, di cui 1,8 destinati all'agenzia regionale. Diversi i temi: dall'analisi dell'evoluzione dei cambiamenti climatici nell'Adriatico all'aumento della conoscenza dell'ambiente marino fino all'analisi dei rumori subacquei. Presente il comandante della Capitaneria, l'ammiraglio Vincenzo Vitale, che ha lamentato per l'Adriatico «la mancanza di un accordo con i paesi vicini, Slovenia e Croazia», nei casi d'intervento delle forze preposte in mare. A dargli man forte l'assessore regionale all'Ambiente, Fabio Scoccimarro, che ha auspicato l'organizzazione il prossimo anno di «una mini conferenza di Parigi per l'area mitteleuropea». Nota positiva: il 6 e il 7 settembre le analisi Arpa hanno confermato la balneabilità di tutti i tratti di costa regionali e delle acque interne dedicate alle attività ricreative.—

I progetti europei per la salvaguardia del mare sono stati il focus del quinto appuntamento con “A misura di mare” di Arpa FVG

29/09/2021

Si è tenuto lunedì 27 settembre il quinto appuntamento del ciclo di incontri **“A misura di mare”, organizzato da Arpa FVG** in collaborazione con l’Autorità di sistema portuale del mare Adriatico Orientale. I **Progetti Europei in alto Adriatico** sono stati il focus dell’evento.

I tecnici di Arpa FVG coinvolti in diversi Progetti Europei hanno illustrato gli **obiettivi, gli sviluppi, le potenzialità e le ultime novità** nei diversi settori. Presente anche l’Assessore regionale all’ambiente e il Contrammiraglio Vincenzo Vitale della Capitaneria di Porto che ha evidenziato le problematiche legate alla **gestione delle emergenze** in un territorio come il Friuli Venezia Giulia, dove ci sono diversi Stati confinanti, sottolinenado l’importanza di **creare collaborazioni stabili ed efficaci.**

La partecipazione a **progetti di cooperazione internazionale** proposti dalla comunità europea rappresentano **un’opportunità** e una fonte primaria di finanziamenti per gli enti tecnico-scientifici, comprese le pubbliche amministrazioni. Oltre alla messa a disposizione di una adeguata **dotazione finanziaria**, essi consentono prioritariamente di avviare delle **collaborazioni stabili** tra partner, che spesso proseguono anche oltre la scadenza dei progetti medesimi.

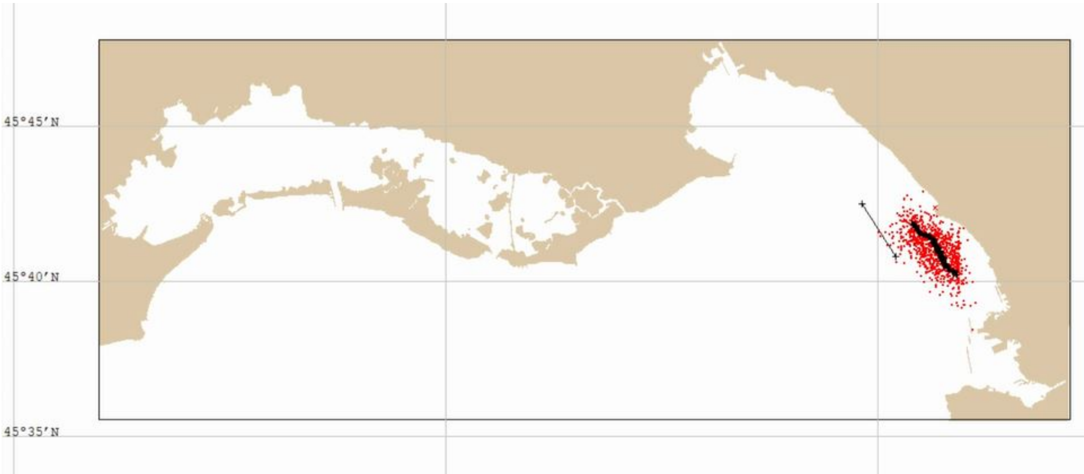
In questo contesto Arpa FVG ha aderito a numerosi progetti afferenti al **Programma Interreg Italia-Croazia** che hanno al centro il **Mare Adriatico**, un bacino ricco sotto vari aspetti: per la biodiversità degli ecosistemi marini, per gli scambi commerciali, per il

Il Programma Interreg Italia-Croazia è lo strumento a supporto della cooperazione tra i due territori. L’intera area del programma si estende su un totale di 85.562 km^2; il budget totale di 236,8 milioni di € consente agli stakeholder regionali e locali di scambiare conoscenze ed esperienze, sviluppare e implementare prodotti e servizi, sostenere gli investimenti attraverso la creazione di nuovi modelli di business, testare la fattibilità di nuove politiche avente come fine ultimo il **miglioramento della qualità e delle condizioni di vita dei cittadini residenti nell’area**.

Arpa Friuli Venezia Giulia ha aderito a 6 progetti, che consentono di ottenere nell’arco temporale 2019-2022 circa 1,8 milioni di € da destinare all’acquisto di sofisticate attrezzature di monitoraggio e all’acquisizione di tecnici specializzati per sviluppare gli ambiziosi progetti in programma.

Di seguito un breve focus sui quattro principali Progetti di cui Arpa FVG è partner attivo.

Firespill – Radar, droni e *drifter* per seguire gli idrocarburi in mare



Il progetto riguarda i rischi naturali di origine antropica e di origine naturale e si pone l’obiettivo di **aumentare l’efficacia di risposta transfrontaliera alle emergenze**. Nell’ambito del progetto, l’impegno di Arpa FVG si focalizza sulle emergenze ambientali causate dallo sversamento di idrocarburi in mare, sinteticamente l’Oil Spill. Su questo progetto l’impegno dell’Agenzia per l’ambiente è duplice e prevede sia l’installazione di nuove e moderne attrezzature di monitoraggio, sia lo sviluppo della modellistica ambientale.

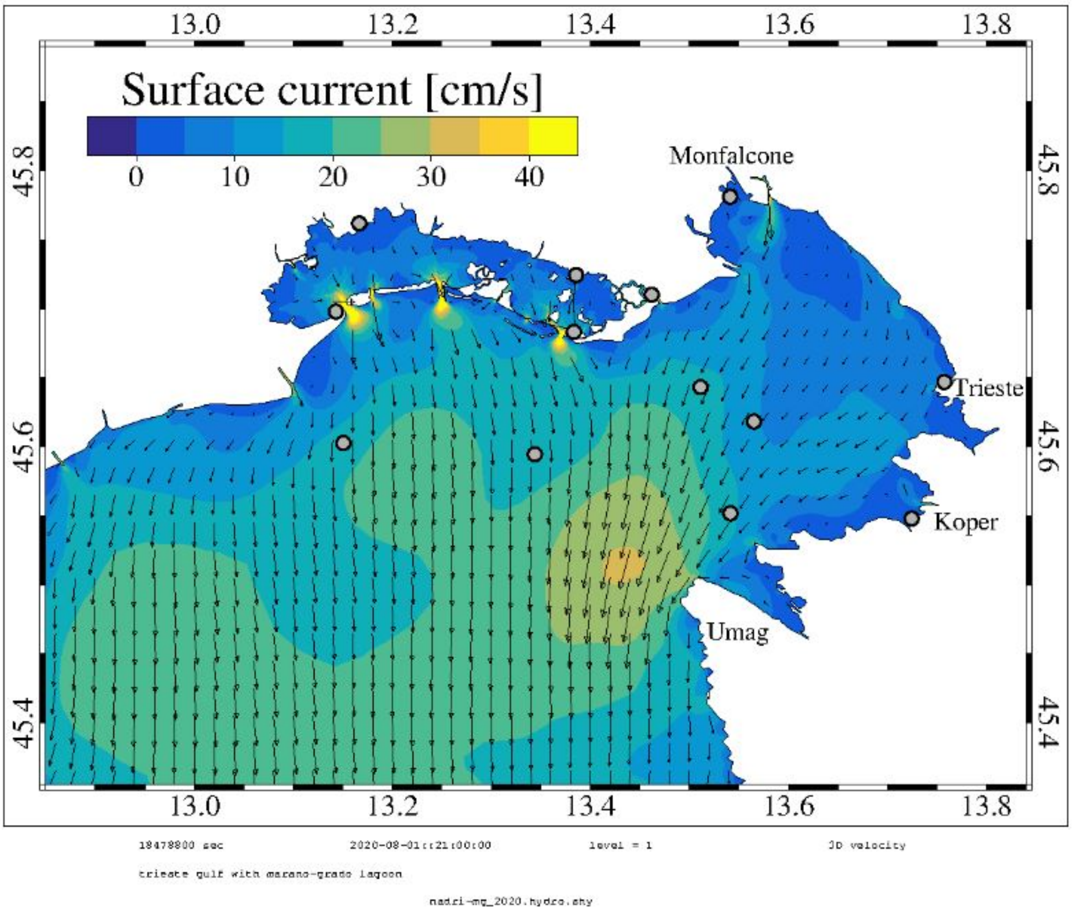
Arpa FVG ha già avviato l’iter per l’acquisto di un **radar** meteo-marino **per monitorare le correnti superficiali e l’altezza delle onde**. Il radar verrà collocato nella **Diga vecchia** in forza di una convenzione, siglata in data odierna, con la Lega navale di Trieste concessionaria dell’area.

Con il progetto verranno anche acquisite altre strumentazioni, tra cui **due droni** per i monitoraggi dall’alto delle macchie di inquinanti in mare, **tre *drifter* e una sonda per la misura degli idrocarburi**.

delle macchie oleose sversate ed ha già sviluppato, tramite il proprio centro di modellistica ambientale, un’importante esperienza.

L’acquisizione del nuovo radar di misura e delle altre attrezzature aumenteranno la capacità di analisi e di previsione di questi eventi. A tale proposito il centro di modellistica ambientale di Arpa ha acquisito due modelli di simulazione in grado di prevedere e seguire passo passo il percorso delle macchie oleose. Gli stessi modelli di simulazione possono essere utilizzati per definire le aree di vulnerabilità nel caso di incidenti da Oil spill.

Adriaclim – Cambiamenti climatici e scenari futuri



Il 9 agosto 2021 è stato presentato il primo volume del 6° Rapporto di valutazione dell’IPCC (*Intergovernmental Panel on Climate Change*) sui **cambiamenti climatici**, un nuovo passo in avanti per la comprensione del fenomeno, delle sue cause e delle sue conseguenze. Il rapporto propone un’analisi di come e perché il clima è cambiato e come potrà cambiare in futuro, a seconda delle scelte che faremo in questi anni.

Il progetto Adriaclim ha lo scopo di **analizzare e modellizzare l’evoluzione dei cambiamenti climatici nel mare Adriatico e lungo le sue coste** per produrre informazioni utili alla stesura di piani di adattamento agli impatti locali dei cambiamenti climatici globali.

Arpa sta perfezionando un modello oceanografico ad alta definizione per simulare lo scenari del futuro, valutando quindi gli impatti dei cambiamenti climatici in Friuli Venezia Giulia.

Cascade – Alla ricerca di specie in via di estinzione

Il progetto Cascade ha lo scopo di aumentare la conoscenza dell’ambiente marino e costiero dell’Adriatico, integrando misure e simulazioni numeriche. Le informazioni acquisite saranno impiegate per valutare il livello di vulnerabilità della biodiversità dell’ecosistema, con l’obiettivo finale di **ripristinare le specie in via di estinzione e sostenere la gestione integrata.**

Con le risorse messe a disposizione dal progetto, Arpa FVG ha realizzato due importanti attività: il **monitoraggio di due specie ritenute scomparse nel Golfo di Trieste** e l’**installazione di una rete di monitoraggio nella laguna di Marano-Grado**.

I monitoraggi hanno interessato la “zona di marea” lungo il litorale roccioso che va dal Villaggio del Pescatore fino a Muggia. Le specie oggetto dei campionamenti sono state il *Fucus virsoides*, un’**alga bruna** relitto dell’ultima glaciazione e il *Gobius cobits* (o **Ghiozzo testone**), un pesce che nidifica negli anfratti rocciosi, considerato in via d’estinzione in queste zone a causa del disturbo delle aree di riproduzione e dalla pressione della pesca dilettantistica.

Grazie ai monitoraggi Arpa ha accertato che **il Ghiozzo testone è ancora presente nel nostro litorale**, mentre **non** è stata **rinvenuta l’alga bruna**.

Il progetto Cascade ha permesso, inoltre, la creazione di una rete di stazioni per il monitoraggio delle acque lagunari, grazie al posizionamento in **tre** punti della Laguna di Marano-Grado di altrettante **sonde multiparametriche**.

temperatura. I dati vengono registrati ogni 15 minuti ed inviati ogni 12 ore ai tecnici di Arpa per l'elaborazione e per il perfezionamento dei modelli previsionali dell'Agenzia.

Soundscape – Il rumore subacqueo, una nuova frontiera d'indagine

Il Mare Adriatico settentrionale è un'area fortemente colpita dall'aumento del traffico marittimo, dal turismo e dello sfruttamento delle risorse, pur avendo una biodiversità molto vulnerabile. L'obiettivo principale del progetto è creare una cooperazione tecnica, scientifica e istituzionale transfrontaliera per monitorare e valutare il possibile **impatto del rumore subacqueo sull'ecosistema marino**.

Il suono rappresenta infatti il più comune e anche il più importante mezzo di comunicazione per le specie acquatiche poiché si propaga molto più velocemente in acqua rispetto che in aria (5 volte più veloce). I suoni vengono utilizzati dagli animali per orientarsi, per cacciare, comunicare, riprodursi e proteggersi in un ambiente con scarsa o totale assenza di luminosità. Si possono udire quindi **suoni biologici**, prodotti dalle specie marine, come pesci, gamberetti e delfini.

Sott'acqua sono però presenti anche **suoni** cosiddetti **geofisici**, prodotti dalle onde, dal vento, dalla pioggia o dai terremoti e con l'arrivo dell'uomo, anche i **suoni antropici**, prodotti dalle attività umane in mare, compreso il traffico marino.

Il rumore introdotto dall'uomo sott'acqua può interferire negativamente con la comunicazione, il comportamento, la *fitness* e la sopravvivenza delle specie.

Purtroppo la disponibilità di **dati sul rumore subacqueo è scarsa** o molto frammentata. A tal fine Arpa FVG già a partire dal 2012 ha avviato attività di monitoraggio del clima acustico subacqueo nelle acque regionali e nel 2019 ha aderito al progetto Interreg Soundscape.

I fondi stanziati dal progetto Saundscape hanno permesso di installare ed attivare per la

Una di queste sonde è stata posizionata da Arpa FVG nel punto più profondo del Golfo di Trieste in prossimità della **meda oceanograficaPaloma, a 25 m di profondità**. I monitoraggi sono iniziati nel febbraio 2020 e continuano ancora oggi. I dati acustici, raccolti mensilmente, hanno prodotto oltre 5000 ore di registrazione.

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D.2.2.3 Publication

PP1 – PP CNR ISMAR

Article in scientific journal MDPI

Author(s)	Alvise Benetazzo, Silvio Davison, Francesco Barbariol, Paola Mercogliano, Chiara Favaretto and Mauro Sclavo
PPs	1
Title	Correction of ERA5 Wind for Regional Climate Projections of Sea Waves
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Correction of ERA5 Wind for Regional Climate Projections of Sea Waves

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(This article belongs to the Section **Oceans and Coastal Zones (/journal/water/sections/Oceans_Coastal_Zones)**)

Abstract

This paper proposes a method to infer the future change in the wind-wave climate using reanalysis wind corrected to statistically match data from a regional climate model (RCM). The method is applied to the sea surface wind speed of the reanalysis ERA5 from the European Centre for Medium-Range Weather Forecasts. The correction is determined from a quantile mapping between ERA5 and the RCM at any given point in the geographical space. The issues that need to be addressed to better understand and apply the method are discussed. Corrected ERA5 wind fields are eventually used to force a spectral wave numerical model to simulate the climate of significant wave height. The correction strategy is implemented over the Adriatic Sea (a semi-enclosed basin of the Mediterranean Sea) and includes the present-day period (1981–2010) and the near-future period (2021–2050) under the two IPCC RCP4.5 and RCP8.5 concentration scenarios. Evaluation against observations of wind and waves gives confidence in the reliability of the proposed approach. Results confirm the evolution toward an overall decrease in storm wave severity in the basin, especially under RCP8.5 and in its northern area. It is expected that the methodology may be applied to other reanalyses, RCMs (including multi-model ensembles), or seas with similar characteristics.
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Keywords: ERA5 (/search?q=ERA5); wind waves (/search?q=wind%20waves); Adriatic Sea (/search?q=Adriatic%20Sea); sea states (/search?q=sea%20states); bias correction (/search?q=bias%20correction)

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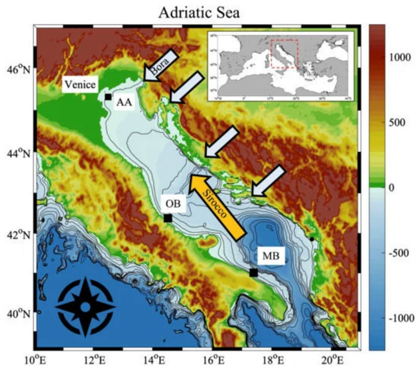

Figure 1

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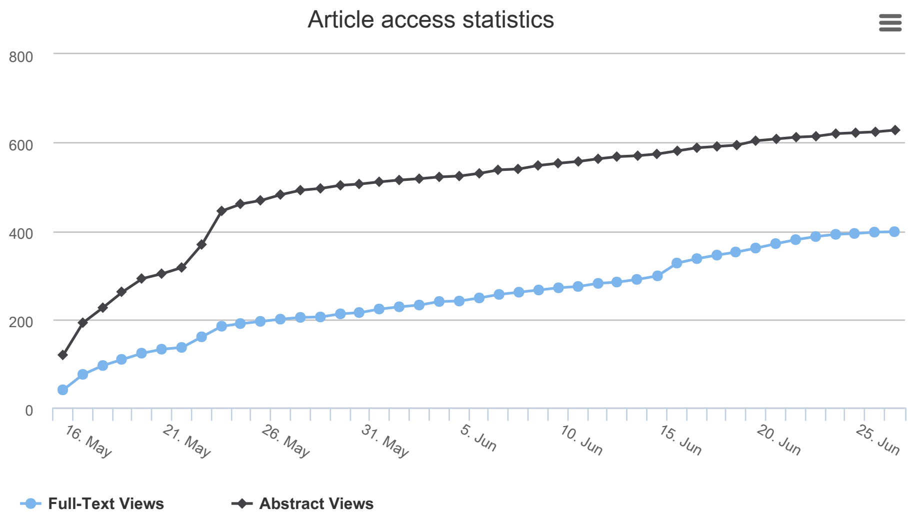

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Venice as a paradigm of coastal flooding under multiple compound drivers

Christian Ferrarin, Piero Lionello, Mirko Orlić, Fabio Raicich & Gianfausto Salvadori

Scientific Reports **12**, Article number: 5754 (2022)

Abstract

Full comprehension of the dynamics of hazardous sea levels is indispensable for assessing and managing coastal flood risk, especially under a changing climate. The 12 November 2019 devastating flood in the historical city of Venice (Italy) stimulated new investigations of the coastal flooding problem from different perspectives and timescales. Here Venice is used as a paradigm for coastal flood risk, due to the complexity of its flood dynamics facing those of many other locations worldwide. Spectral decomposition was applied to the long-term 1872–2019 sea-level time series in order to investigate the relative importance of different drivers of coastal flooding and their temporal changes. Moreover, a multivariate analysis via copulas provided statistical models indispensable for correctly understanding and reproducing the interactions between the variables at play. While storm surges are the main drivers of the most extreme events, tides and long-term forcings associated with planetary atmospheric waves and seasonal to inter-annual oscillations are predominant in determining recurrent nuisance flooding. The non-stationary analysis revealed a positive trend in the intensity of the non-tidal contribution to extreme sea

levels in the last three decades, which, along with relative sea-level rise, contributed to an increase in the frequency of floods in Venice.

Introduction

Coastal flood events are among the most disastrous natural phenomena of major risk to the safety and sustainability of coastal communities worldwide. Coastal flood risk has increased world-wide in the last decades, mostly due to mean-sea-level rise[1,2,3,4]. Coastal flooding is determined by anomalously high sea levels which are the sum of several tidal and non-tidal processes acting at different temporal and spatial scales[5]. Meso-scale atmospheric disturbances, synoptic-scale phenomena, seasonal oscillations and planetary atmospheric waves generate sea-level disturbances at different frequencies. Seiches, river floods, ocean waves, inter-annual and inter-decadal dynamics and relative sea-level rise can also contribute to the total sea level.

In this study, we analyze the long term sea-level time series recorded in the low-lying historical city of Venice (Italy), located in the northern end of the Adriatic Sea, a semi-enclosed regional basin with one of the largest tidal range (the height difference between high tide and low tide) and extreme sea levels (ESLs) in the Mediterranean Sea[6]. As a result of the devastating series of floods occurring in November 2019[7], Venice has been defined as the “canary in a coal mine” for coastal flooding worldwide[8], also because with 15 flood events in a month it experienced something similar to what the flooding frequency will be in the future with 30 cm of sea level rise[9]. The city of Venice represents a key study site for coastal flooding for several reasons: (i) it has a long-lasting record of sea-level observations (since 1872), (ii) Venice is frequently exposed to floods, locally called *Aqua Alta* (literally, high water), (iii) the frequency of flood events has increased over time and is likely to continue increasing in the future mainly due to sea-level rise and subsidence, (iv) it has a worldwide recognized relevance as the site is present in the UNESCO world heritage list (https://whc.unesco.org/en/list/394/), (v) an experimental and extensive flood protection plan based on the MoSE mobile barrier system has been designed (https://www.mosevenezia.eu/).

The unexpected and peculiar characteristics of November 2019 floods[7,8] reveal the need to further explore the processes determining coastal flooding. Interestingly enough, such a phenomenon belongs to the class of so-called compound events, of utmost interest in recent geophysical research[10]. The specific objectives of the present research are to (i) investigate the relative importance of the different contributions to extreme sea levels, (ii) study their temporal change, (iii) examine their non-linear interactions and (iv) estimate the probability of occurrence of extreme events generated by the superposition of multiple drivers. In this study, Venice is taken as a paradigm of coastal flooding whereby the methodology proposed here for the analysis of extreme sea levels may be tuned and applied to other locations worldwide.

Sea level data and physical processes at work

Regular instrumental observations of the sea level in the city of Venice began in 1871 at the tide gauge named "Punta della Salute". The sea-level records were referenced to mean sea level (MSL) over the period 1885–1909. This datum is locally called "Zero Mareografico Punta della Salute" (ZMPS)[11]. In this study, we analyze the sea-level time series recorded in Venice from 1872 to 2019 (148 years) consisting of: the sequence of water level maxima and minima from 1872 to 1939 (generally four values per day, that is on average 6-hourly measurements); hourly values from 1940 to 2009; 10-min values from 2010 to 2019. Since October 2020, the mobile barriers at the three inlets (MoSE) have started to be in a pre-operational phase closing the lagoon during severe events and protecting Venice from flooding[12]. Therefore, this study presents the most comprehensive analyses of ESLs within Lagoon of Venice but, because of the MoSE barriers, it may not be extended into the future.

According to Orlić[13] and Lionello et al.[14], we here consider the sea level in Venice as the superposition of the following contributions attributable to different physical processes:

- *astronomical tide*: a mixed semidiurnal tide prevails in the northern Adriatic Sea with eight principal tidal constituents, four semi-diurnal and four diurnal[15]. The tidal range reaches almost 1 m during peak springs;

- *storm surge*: the response of the sea level to synoptic air pressure and wind forcing. In Venice, storm surge events are mostly driven by the south-easterly wind (Sirocco) blowing over the Adriatic Sea or a combination of north-easterly wind (Bora) over the northern Adriatic Sea and Sirocco over the south Adriatic Sea[16];

- *seiches*: free sea-level oscillations in the Adriatic Sea with periods determined by the normal modes of the basin that are mostly triggered by previous storm surges when the atmospheric forcing vanishes. The decay time of these oscillations is estimated at about 3 days[17,18]. The two main modes have periods of about 21.8 and 10.7 h, which are close to the periods of the principal diurnal and semi-diurnal tidal constituents, respectively[15];

- *meteotsunami*: large waves driven by mesoscale atmospheric pressure disturbances often associated with fast-moving weather events, such as severe thunderstorms, squalls, and other storm fronts. Such high-frequency sea-level oscillations are generated by resonance in the open sea when the speed of propagation of the perturbation approaches that of the shallow-water barotropic waves. In harbours and bays, coastal resonance may also play an important role in the local amplification of meteotsunami waves[19];

- *local wind setup within the lagoon*: with strong NE (Bora) or SE (Sirocco) winds, the difference between sea levels in the south and the north side of the lagoon may exceed 50 cm[20]. Even if Venice city centre is little affected by these fluctuations, since it is close to the node of the oscillation of the water level in the lagoon, a high-fequency wind setup (of the order of 10 cm) has been observed under strong SW winds[7];

- *PAW surge*: long-lasting sea-level anomalies generated by disturbances of air pressure and wind associated with planetary atmospheric waves (PAW) having characteristic wavelengths ranging from 6000 to 8000 km[21]. These events may result in a prolonged interval of high sea level in the northern Adriatic Sea, which provides the long-term preconditioning for many flood events in Venice[22];

- *inter-decadal, inter-annual and seasonal (IDAS) sea-level variability*: the occurrence of ESL also displays marked seasonal to decadal variability associated with large scale atmospheric and oceanic circulation patterns[9,15]. According to Valle-Levinson et al.[23], interannual variability of MSL in the northern Adriatic can be mostly explained by astronomic forcing associated with lunar precessions, solar activity, and the interaction, or interference, between these factors;

- *relative sea-level rise (RSLR)*: a long-term process connected to both climatic change and land subsidence[9]. In the 1872–2000 period, the combined effect of the subsidence and sea-level rise resulted in a relative rise of 31 cm[24], determining a substantial increase in the frequency of floods in Venice[16]. Mean sea level of 2019 is 0.34 m above ZMPS.

All listed contributions have values of the order of tens of centimetres (storm surge is potentially the largest one, exceeding one meter in extreme cases). Other factors, like river floods, earthquake tsunamis and waves are not relevant for the sea-level variability in Venice[14]. For simplicity, the combination of the meteorological contributions with periods lower than 10 days excluding the seiches (storm surge, mesoscale atmospheric variability set-up including meteotsunamis and local wind setup) is collectively termed "storm surge" in this paper when no distinction is possible among the different drivers.

Results and discussion

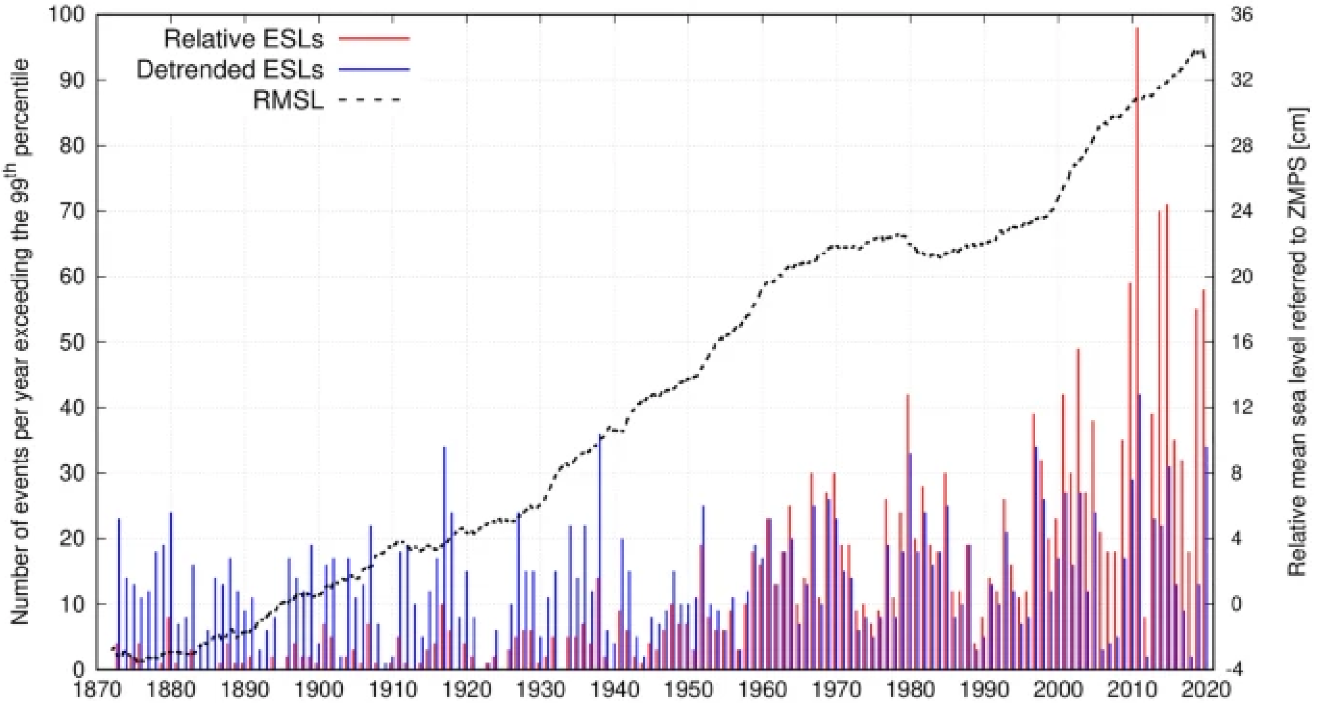
Identification of extremes

In this work, we are interested in extreme sea-level events driven by any combination of the tidal and non-tidal components. A peak over threshold method is often used to identify extreme sea levels from tide gauge observations[25]. However, selecting an appropriate threshold is still challenging and can bias the statistical assessment. In

Venice, a value of 1.40 m above ZMPS is the threshold commonly used for identifying exceptional events (https://www.comune.venezia.it/it/content/le-acque-alte-eccezionali). However, with such a high threshold few data sets (25 events in the 1872–2019 period[26]) would be included in the analyses. Other arbitrary thresholds can be used, such as a water height of 1.10 m above ZMPS, which is the height at which the MoSE barriers will be activated to prevent the flooding of the historical city[12].

Relative sea level in Venice has been strongly influenced (i.e. raised) by subsidence and eustasy (1.30 and 1.23 mm/year on average over the 1872–2019 period, respectively[9]). Therefore, the extreme value selection was based on the distribution of the sea levels detrended for RSLR by subtracting the 19-year centered running mean (black dashed line in Fig. 1). Then, the 99th (0.70 m), 99.5th (0.77 m) and 99.9th (0.95 m) percentiles of sea levels are used here for identifying extreme values (2012, 1005 and 201 events, respectively). As shown in Fig. 1, the detrended dataset presents a much more homogeneous distribution of ESL events over time with respect to the relative (uncorrected for RSLR) sea-level dataset.

Figure 1



Number of events per year exceeding the 99th percentile threshold in the relative (red bars) and detrended (blue bars) sea-level datasets. The time evolution of the relative mean sea level (19-year running mean) is shown as a black dashed line.

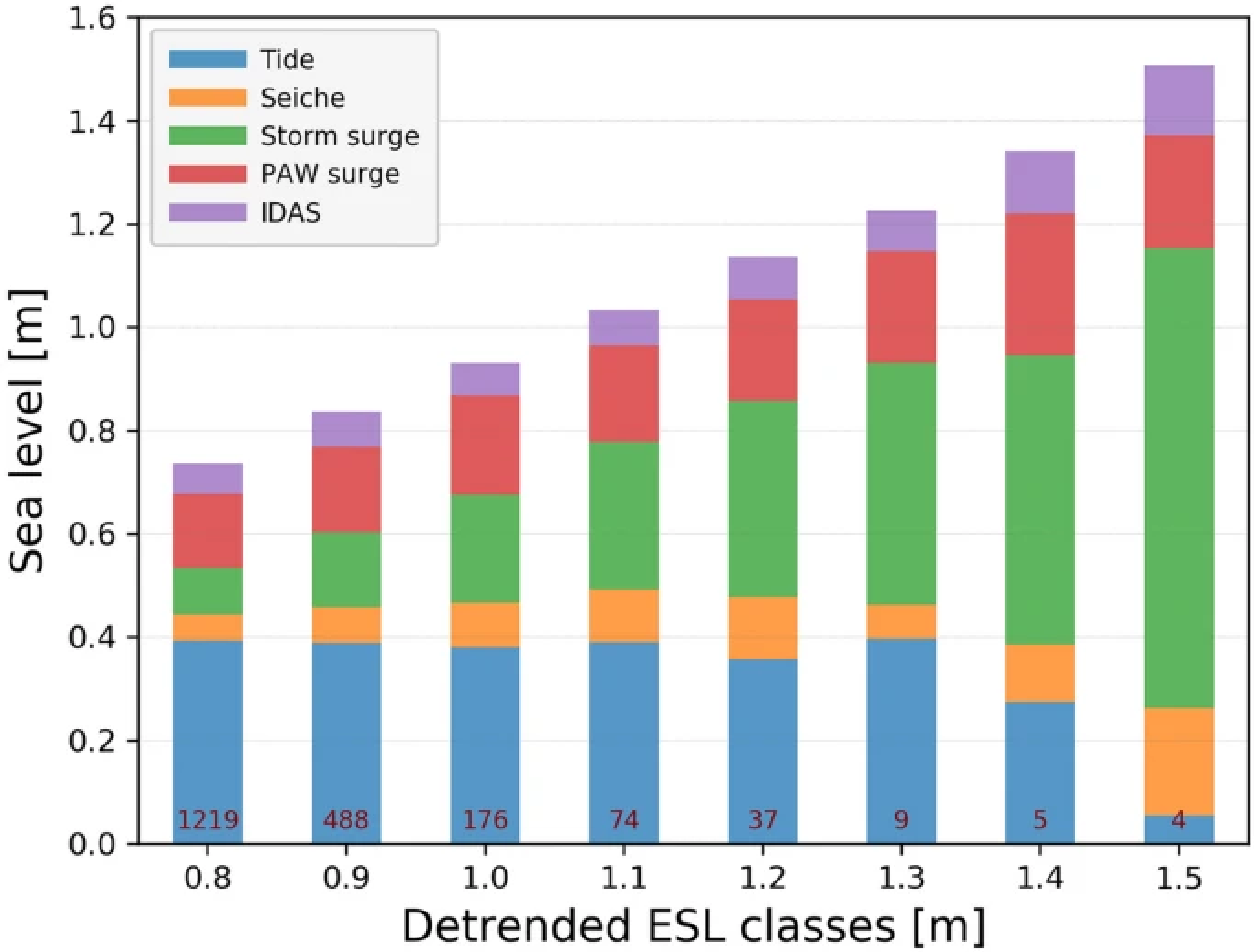
Drivers of extreme sea levels

Tidal harmonic analysis and digital filters were used to separate the sea-level time series into different water level components (tide, storm surge, high-frequency surge, seiches, PAW surge, IDAS). A detailed description of the decomposition procedure is reported in the Methods section. Extreme sea levels in Venice turned out to be driven mostly by the non-tidal residual (i.e. >50%) with the astronomical tide contributing on average 49, 44 and 36% of ESLs when considering the 99th, 99.5th and 99.9th percentile datasets, respectively (Table 1). These results agree with other studies[26] showing that the highest sea levels are mainly dominated by the non-tidal residual (NTR), while tide plays an important secondary role.

Table 1 Mean contribution (in %) of the different drivers of ESLs defined according to the 99th, 99.5th and 99.9th percentile datasets. Tide and NTR contributions are computed with respect to the total sea level, while the other non-tidal contributions are computed with respect to NTR.

The non-tidal residual of the extreme sea levels could be attributed mostly to PAW surge and storm surge, with the latter component becoming dominant for the most extreme events. In general, the relative role of low-frequency signals (PAW surge and IDAS) decreases with the severity of the event, and the opposite occurs for the short term components (with periods shorter than 10 days: seiche and storm surge). However, as illustrated in Fig. 2 which reports the relative contribution of the drivers for different values of the ESLs, this does not correspond to a decrease of the absolute values of the PAW surge and IDAS terms, the sum of which, on average, increases from 20 to almost 40 cm towards the most severe events. Positive IDAS ($\max = 0.26$ m) and PAW surge ($\max = 0.43$ m) oscillations could result in a prolonged interval of high sea level in the northern Adriatic Sea, as observed in November 2019[7]. These results confirm previous studies highlighting the important role of low-frequency fluctuations in providing favourable conditions for flooding events in the northern Adriatic Sea[22]. Such a strong contribution of the low-frequency oscillations to the Venice floods emerged in the last decades in association with the high mean relative sea level. For more details about the inter-decadal, inter-annual and seasonal sea-level variability, the reader may refer to the review paper by Zanchettin et al.[9].

Figure 2



Mean contribution (in m) of the different drivers of ESLs subdivided into 10 cm bins. The red labels inside the bars indicate the number of events per class.

The storm surge contribution varies from 0.10 to 0.70 m with a clear positive trend towards the most extreme events. The highest storm surge event (1.07 m) occurred on 4 November 1966, when the total sea level reached the maximum value ever recorded in Venice (1.94 m above ZMPS). Other events with extreme storm surge contributions occurred in 1979 (0.75 m), 2018 (0.74 m) and 1879 (0.74 m). All these events were driven by strong SE winds blowing over the whole Adriatic Sea and determining the rise of the sea level and high waves in the northern end of the basin[16].

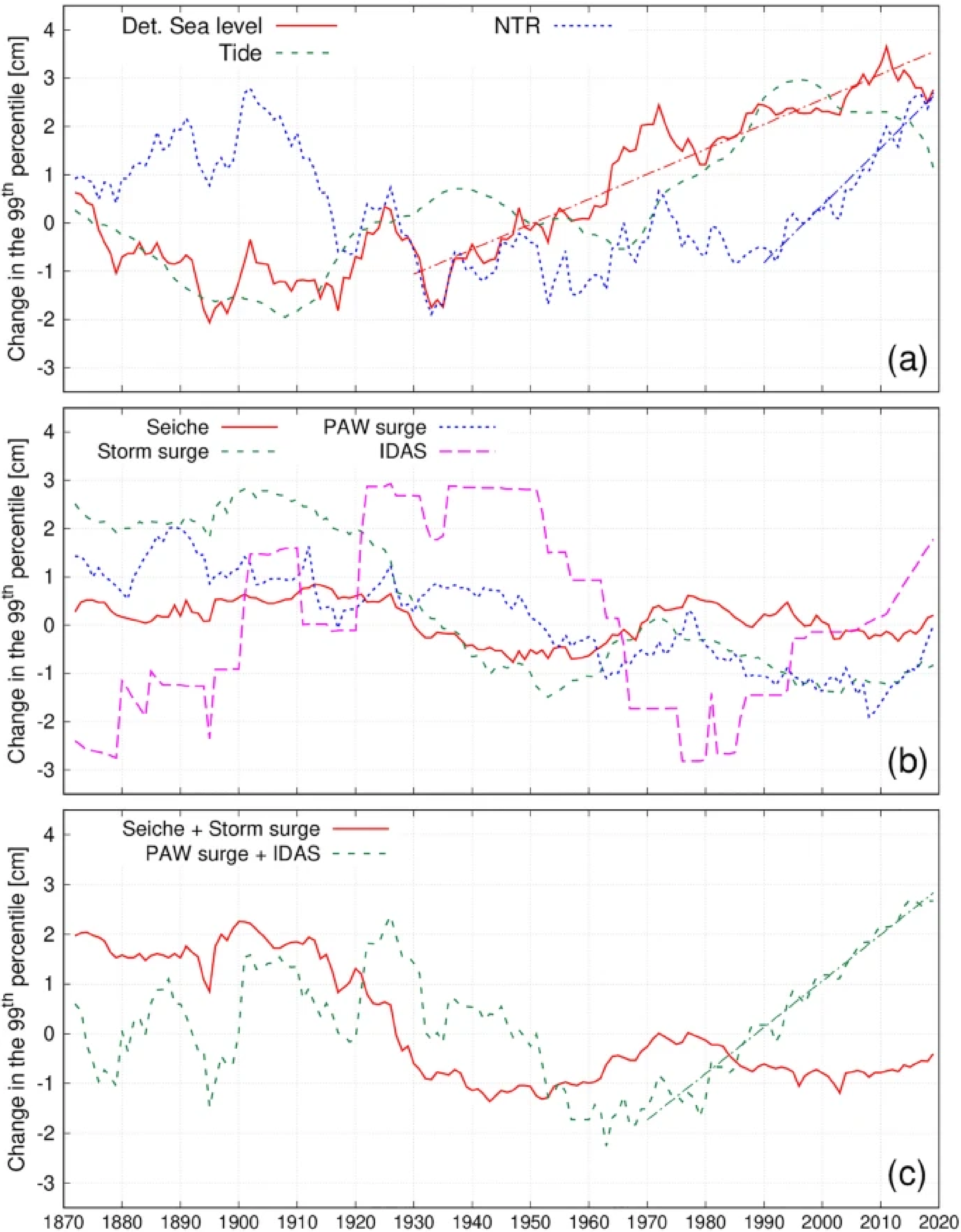
On average, seiches have a contribution that increases in magnitude from 0.05 to 0.21 m with the severity of the event (Table 1, Fig. 2). Seiches are responsible for extreme sea-levels usually after a substantial surge event, which triggers fundamental oscillations of the Adriatic basin. Indeed, high seiches were registered in the days succeeding the 4 November 1966 and other storm surge events[17]. However, a very high seiche oscillation (0.43 m) occurred in December 2019 without a substantial storm surge. It was probably triggered by a SE wind followed by an NW wind after about 10–11 h (i.e., half of the period of the fundamental Adriatic seiche). Such resonant excitation with two relatively week impulses, but perfectly timed (i.e. a typical compound event), caused an oscillation which represented more than half of the non-tidal residual signal.

The 1940–2019 hourly time series only was used for analyzing sea level high-frequency fluctuations with a period lower than 10 h. The maximum value of this component (0.36 m) was registered on 12 November 2019, due to the combined action of a meteotsunami propagating along the coast (0.27 m) and a local surge inside the lagoon (0.09 m), both induced by a meso-beta scale atmospheric disturbance travelling along the north-eastern Adriatic coast[7]. The database shows no evidence of other high-frequency events of similar magnitude and only six events with high-frequency surges equal to or higher than 0.15 m were identified. Therefore, according to the analysis of the 1940–2019 dataset, the meteotsunami that hit the coast in front of Venice on 12 November 2019 represents an extremely rare episode.

Non-stationary analysis

Temporal changes in extreme sea levels over the 1872–2019 period were investigated by computing the 99th percentile of sea level maxima on a 30-year centered running window[25] (Fig. 3a). Orlić et al.[27] showed that the 30-year window suppresses the decadal-scale variability of the Adriatic sea levels while it does not drastically reduce the length of the time series. This implies that the multidecadal variability remains in the filtered time series and has to be allowed for while interpreting the results obtained from them. The 99th percentile of the detrended sea levels (red line) fluctuated around a constant value from 1872 to 1930 and then subsequently increased. We also investigated the 99th percentile evolution of the different contributions, which, even if their values cannot be summed linearly, may provide information on the temporal changes of the processes at work. Changes in the 99th percentile of the tidal (green dashed line) and non-tidal residual (blue dotted line) components showed almost opposite behaviours with a decrease (increase) phase from 1872 to 1910, an increase (decrease) phase till 1990 and then a decrease (increase) phase again in the last decades. The general increase in the amplitude of major tidal constituents is mostly due to the anthropogenic interventions that altered the lagoon's morphology during the last two centuries (salt marsh reduction, dredging of navigational channels, groundwater and gas extraction, inlets' modifications). These morphological changes resulted in a reduction of the dissipative forces due to friction, with the consequent amplification, due to resonant processes, of the incoming tidal wave while it propagates inland[28]. Changes in the detrended NTR 99th percentile—which includes the contribution of storminess (storm surge) and flood preconditioning (PAW surge and IDAS)—show an increasing trend in the last three decades.

Figure 3



Temporal changes of the 99th percentiles of the different drivers, computed with respect to the long-term mean value. The dash-dotted lines indicate the trends discussed in the text (slope statistically significant at the 0.05 level).

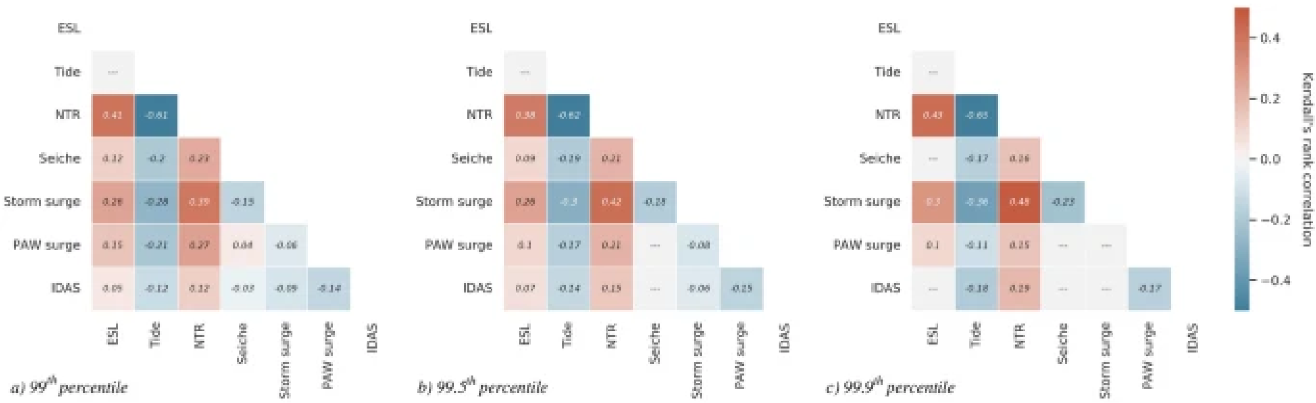
Slightly negative tendencies of the 99th percentile can be identified for the storm surges and the PAW surges, while no clear long-term trend can be detected for the other components (Fig. 3b). Interestingly enough, the analysis of the percentile evolution of the combined contributions referring to short-term (period < 10 days, i.e. seiche plus storm surge) and long-term (period > 10 days, i.e. PAW surge plus IDAS) revealed that the increase of the 99th percentile of the non-tidal residual in the last three decades seems to be mostly due to changes in the IDAS and PAW surge (Fig. 3c), the combination of which determines the large-scale dynamical precursor for flooding in Venice. The PAWs, and the related PAW surges, could change considerably with the global warming: since the latter is much more pronounced in the polar than in the equatorial regions, the amplitudes of PAWs increase and their speeds decrease[29] implying that the amplitudes of PAW surges increase and that these surges last longer. The seasonal analysis of the 99th percentile revealed that the data of October, November and December (when most of the flooding events occur[16]) have a more marked increasing trend for both the detrended sea level (8 cm since 1880) and the NTR component (about 10 cm since 1930). The detected changes in the extreme values of the different components are relatively small (within a few cm for all terms) when compared to changes in relative mean sea level (about 0.37 m in 148 years; black line in Fig. 1).

Non-linear interactions (NLI)

Even if surges can occur in association with any tide, tidal and non-tidal components have a certain degree of interaction in shallow water areas with large tidal excursions where shoaling and other non-linear effects are considerable[30,31]. Therefore, tides and storm surges may mutually affect each other’s phase and this interaction may lead to high surges often occurring during low water and before high water (HW) than at HWs[30,32] during flood tides. Moreover, wind stress is more effective at raising the sea surface in shallow water and therefore one would expect any surge to be largest at low water[30].

The statistical correlation between tide and non-tidal residuals obtained decomposing tide gauge records has often been used as a measure of the influence of non-linear interactions on extreme sea levels[25,33]. Our statistical analysis, even if performed over a longer timeseries than used in previous studies, produced similar results showing a marked negative correlation between tide and NTR which slightly increases with the severity of the events. Indeed, the non-parametric Kendall's rank correlation \(\tau\), an association measure ranging between \((-1,1)\), takes on values of \(-0.61, -0.62\) and \(-0.65\) when considering, respectively, the 99th, 99.5th and 99.9th percentiles as thresholds for identifying extreme sea levels (Fig.4): this means that the variables are statistically *discordant*, i.e. small (large) values of one variable are likely to be associated with large (small) values of the other, and vice-versa. Tides were found to be negatively correlated with all factors affecting extreme sea levels. Seiches are anticorrelated with storm surges, which trigger free oscillations in the Adriatic Sea. However, since the decay time of these oscillations is 3–4 days, they can overlap with a new storm surge causing very high sea levels in the northern Adriatic Sea (e.g. on 1 December 2008 and 25 December 2009[18]). Therefore, even if storm surges and seiches are generally out of phase (anticorrelated), joint occurrences of these two factors are possible since the passage of synoptic systems can take place in rapid succession. The different meteorologically-induced sea-level signals (storm surge, PAW surge, IDAS) were weakly (\(|\tau | < 0.2\)) or not correlated with each other, highlighting that, from a statistical perspective, the atmospheric processes evolving at different spatial and temporal scales (mesoscale, synoptic, planetary) act almost independently on the extreme sea levels in Venice.

Figure 4



Kendall's rank correlations among the different drivers for the 99th (**a**), 99.5th (**b**) and 99.9th (**c**) ESL percentiles. Only values statistically significant at the 0.05 level are reported.

In this study, we used the Theory of Copulas[34,35] to identify an appropriate model to capture the dependence structure between the mentioned drivers and combine their joint occurrences to calculate extreme sea levels. We considered ESLs as determined by the sum of tide and NTR, assuming the two variables either (i) as dependent and modelled via a suitable bivariate copula, or (ii) as being independent. Similarly, a multivariate analysis has also been performed considering the ESL determined by the combination of tides, seiches, storm surges, PAW surges and IDAS. Sea level percentiles (99th, 99.5th and 99.9th) are calculated for the dependent and independent artificial samples (for both the 2 and 5 variables cases) and differences between these values are assumed to describe NLI on ESLs[25]. The estimated tide-NTR NLI is sensitive to the considered dataset and ranges from -26 to -52 cm. Similarly to the case with two variables, the NLI estimated from the Copula functions with five variables ranges from -23 to -45 cm. The largest values were found for the most severe events (Supplementary Table S1).

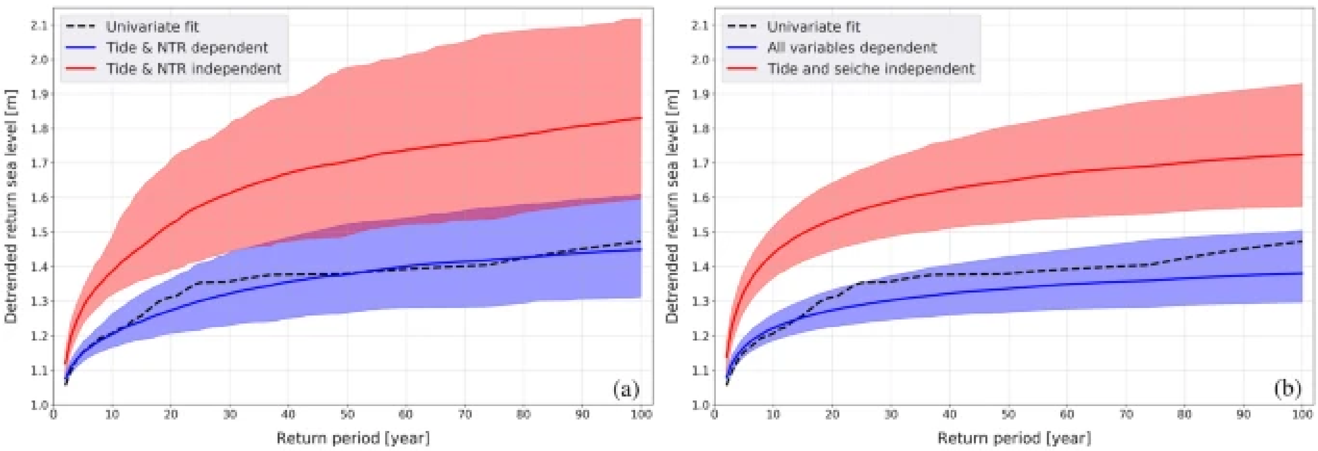
These anti-correlations apparently suggest that some non-linearity is at work in the northern Adriatic Sea and the Lagoon of Venice with the tide having a lowering effect on extreme sea levels. In the northern Adriatic Sea, given the relatively small importance of tidal excursion (about 1 m) as compared to local water depth (average depth of about 35 m), it is reasonable to neglect the effect of tides on storm surge generation and propagation. Similarly, storm surges would not significantly influence the tide. These assumptions have been confirmed by high-resolution numerical studies demonstrating that tide-NTR interactions are negligible in the northern Adriatic Sea, even during the most severe events[14,36,37]. Moreover, a similar tide-NTR anticorrelation was found by analyzing the 1974–2019 sea-level dataset collected by the Acqua Alta oceanographic tower, located in the Gulf of Venice, 15 km offshore the Venetian littoral. Sea-level oscillations in the storm surge frequency band, once they have entered inside the lagoon through the inlets, propagate nearly without modification to the Venice city centre, where residual levels are comparable (apart from the local effect of the wind) to the ones at the inlets with a typical 1-hour delay[38].

The tide-NTR anticorrelation found by the statistical analysis could not, therefore, be fully explained by ocean non-linear processes and results from the fact that, generally, the highest NTRs tend to occur around mid-tide or low-tide rather than at the time of tidal high water. Indeed, in the most extreme storm surge events of 1966, 1979 and 2018, the peak of the storm occurred during low tidal conditions, limiting the already dramatic flooding conditions in Venice. Even if the peak astronomical tides and peak storm surges tend to occur in different parts of the year in the northern Adriatic Sea[32], the observed tide-NTR anticorrelation is an unresolved issue and a clear ocean process-based explanation of it is still missing.

Probability of occurrence of ESLs

The results presented in the previous sections were used to investigate the probability of occurrence of an extreme sea level generated by the combination of the different processes. For return periods (RP) varying from 2 to 100 years, the corresponding design values of ESLs are calculated by aggregating the variables of the simulated vectors of marginal components under the dependent and independent assumptions (Fig. 5). We only present the results of the models based on the 99.9th percentile dataset, which best fits the observations, supporting the fact that the degree of association among the drivers extracted from the most severe events are most appropriate for representing the dynamics of ESLs in Venice Lagoon.

Figure 5



Return sea levels and periods obtained from the univariate fit of ESLs and as modelled considering the combination of two (panel **a**) and five (panel **b**) variables. Model's median (solid line) and 95% confidence interval (band) are shown.

The return sea level determined from the tide-NTR dependent model (blue continuous line in Fig. 5a) well represents the RP statistics extracted from the univariate fit of the detrended sea levels (black dashed line). If the non-linear tide-NTR interactions are not considered (red continuous line in Fig. 5a), the return sea levels are overestimated, which means that extreme sea levels could occur with a higher frequency. As an example, a sea level of 1.4 m would have an RP of about 10 years in the independent case and an RP of more than 100 years in the dependent case. Similar results were obtained considering the aggregation of five variables (tide, seiche, storm surge, PAW surge, IDAS) (Fig. 5b). It is worth noting that, on the one hand, the 5-variables model may account for the simultaneous (compound) effects of the five drivers of interest, and, on the other hand, it has narrower confidence bands with respect to the 2-dimensional (tide-NTR) model.

These results highlight the large influence of the non-linear interactions—mostly linked with the effect of the tide with the other components—on the return sea levels and related occurrence periods. Moreover, there is a large variability in the RP's estimation using different datasets, as highlighted by the values computed for some of Venice's most extreme sea-level events (Supplementary Table S2). To compute the RP of such extreme values, the ESL data have been fitted with different models (see the Methods section) choosing the one that best represents the data. The 1966 event has a return period ranging from 255 to 929 years according to the dataset used in the calculation. The 356 years RP of the 1966 events estimated using the 99.9th percentile dataset is consistent with previous estimations[32,39]. The flooding event of November 2019—second only to the 1966 event—should occur on average once every 92 years.

ESLs and coastal flooding

Every coastal location has site-specific flooding thresholds that can change due to oceanographic drivers, as well as changes in flood defences and coastal morphology[40]. In the ESL analysis presented above, we considered the detrended sea levels for investigating the dynamics of extreme events removing long-term subsidence and eustatic effects. However, when dealing with coastal flooding, the ESL values must be referred to the local relative sea level. The probability of occurrence of a specific flooding level can be easily calculated by shifting the return level/period curves (Fig. 5) to consider past and near-future changes in the relative sea level[3,4,41]. Therefore, the return period of the 1966 flood, which reached the peak water height value of 1.94 m above ZMPS (about 90% of the city flooded), reduces to less than 100 years when considering a relative sea-level 30 cm higher than today. Considering less extreme events, the return period of a water height value of 1.40 m above ZMPS (60% of the city flooded) changed from about 70 years at the beginning of the 19th century to less than 5 years today.

It is important to highlight that the relative role of the different drivers in coastal flooding changes according to the mean relative sea level and the flooding threshold considered. We used to focus our attention on the most extreme events and their consequences on coastal flooding. As shown above, these events were mostly driven by storm surges (e.g. 1966, 1979 and 2018 events). However, it is noteworthy that in Venice even a low level of flood (i.e. nuisance flooding[42], determined by water heights between 1.10 and 1.40 m above ZMPS) has high impacts such as disruption of everyday routine activities and property damages. Such events can be caused by several drivers or their combination (e.g. the sequence of exceptional floods of November 2019[7]), thus increasing the probability of flood occurrence. Indeed, use of different thirty-year time windows revealed:

- 8 nuisance floods in 1890–1919, half dominated by tide (i.e. > 50% of the total sea level) and half by storm surges;
- 44 nuisance floods in 1940–1969, one fifth of which were dominated by storm surges, and tides and long-term fluctuations (IDAS plus PAW surge) representing the largest factor in 73% and 7% of the cases, respectively;
- 172 nuisance floods in 1990–2019, 70% of which were mainly driven by tide, while the long-term fluctuations and storm surge are dominating in 18% and 12% of the cases, respectively.

It is clear that in Venice, as well as in other parts of the world, SLR and subsidence lead to an increase in recurrent flooding at high tide[14,43]. Moreover, secular amplification of tides induced by RSLR and anthropogenic activities also contributed to increasing the flood frequency[28,44]. Therefore, flood risk in Venice increased during the last century and will certainly worsen in the future due to RSLR and especially if the positive trend in the large-scale precursor for flooding (IDAS plus PAW surge; Fig. 4) persists. Even if most of the climatological studies predict attenuation of storm surges[14,45], the number and the duration of flooding events in Venice will increase in the future (exponentially according to Taherkhani et al.[4]), with high impacts on the management of flood defence measures. With a SLR of 50 cm, the MoSE barriers will have to be activated almost every day[4,12], because the tide alone will result in a sea level exceeding the 1.10 m flooding threshold. It is worth stressing that the novel multivariate statistical framework outlined in this work may also provide useful information for improving the short term forecasts for Venice, which are especially important for the operation of the MoSE barriers[46,47].

Conclusions

The major conclusions of this work are summarized in the following points.

1. The spectral decomposition of sea level allows for the quantification of the relative role of the different drivers to ESLs. In the northern Adriatic Sea, storm surges are responsible for the most extreme sea levels but the drivers of coastal flooding in Venice are many and may occur together as compound events. Due to the rise of relative mean sea level, the tide and long-term meteorological components actually play a dominant role in driving recurrent—even unexceptional—floods.

2. The non-stationary analysis revealed an increasing trend in the intensity of the non-tidal contribution to the sea level in the last three decades. Such an evolution could be mostly attributed to changes in IDAS and PAW surges, the combination of which determines the large-scale dynamical precursor for flooding in Venice.

3. Copulas, which account for the statistical dependence among the different contributions to sea level extremes in case of compound events, provide an effective tool for their description, which improves the information given by univariate extreme value analysis. The analysis revealed evidence of significant correlations among the drivers, which have a lowering effect on extreme sea levels and are fundamental for producing a correct estimate of extremes.

4. Statistical correlations derived from tide-gauge records may be misleading in the evaluation of non-linear interactions in shallow water and should not be used to estimate NLI influence on extreme sea levels. In Venice, the tide-NTR anticorrelation results from the fact that, generally, the highest NTRs tend to occurs around mid-tide or low-tide rather than at the time of tidal high water. This topic will need to be further investigated and its understanding is essential from a climate change perspective in which the drivers of ESLs may have a different rate of change.

There is a massive global scientific effort in understanding and managing coastal flooding, one of the main threats to coastal communities especially in the most vulnerable low-lying areas of the world. Many coastal locations, such as Venice, are already experiencing an alarming growth of flood threat due to global warming and consequent rise of the level of the oceans. It is likely that within the next decades what we now consider to be extreme events will happen at every high tide. Obviously, the flood risk strongly depends on site-specific coastal characteristics and protection measures, but also on the processes determining the intensity of the hazards. In this context, Venice is a very important paradigm for coastal flood risk, also because it is already affected by both high-frequent nuisance and rare extreme flood events. The general methodology adopted in this study (not specific for the Lagoon of Venice only) provides new insights into the physical drivers of the extreme sea levels and therefore could add fundamental knowledge to science-based and sustainable flood management strategies all around the world.

Methods

Sea level decomposition

The whole dataset was first interpolated with a monotonic cubic method at 10 min interval and then detrended with a 19-year centered running mean to remove the long-term variability induced by sea-level rise, subsidence, multidecadal variability and non-linear tidal effects of the lunar cycle within the lagoon[28]. As reported by Pirazzoli et al.[32], in this manner extreme sea levels from different years are made "climatically homogeneous" and can easily be compared in spite of relative sea-level changes[9].

The detrended dataset was then processed with a tidal harmonic analysis tool based on the least-squares fitting[48] to separate the tidal from the total sea level. The method considers standard 67 tidal constituents and can deal with an incomplete series of data and with observations at different time intervals. In this study, the whole 1872–2019 dataset has been analysed considering a 19-year running window to account for changes in the tidal characteristics. As reported in Ferrarin et al.[28], the amplitude and phase of the principal tidal components in Venice exhibit a substantial change over the last century, mostly due to anthropogenic interventions. Nodal correction is considered in the processing. At each time step, the difference between the observed total sea level and the tidal value is here called non-tidal residual (NTR).

Once the decomposition of the total sea level has been carried out, we aim to identify the different non-tidal processes based on their characteristic periods[7,14,49]. The contributions of storm surge, PAW surge, mesoscale atmospheric variability (MAV) including meteotsunami, local surge, seiche and IDAS variability were isolated from the detrended NTR using digital filters (low pass, band-pass and high pass) in the time domain exploiting Fourier decomposition. The value separating storm surge and PAW surge was set to 10 days and the corresponding value for storm surge and high-frequency surge (associated with MAV set-up, meteotsunami and local surge within the lagoon) was set to 10 h. The separation between the PAW surges and IDAS variability was achieved by applying a low pass filter with the cut-off period equal to 120 days. The storm surge signal (having a period between 10 hours and 10 days) was further band-pass filtered to extract the seiche activity. These filters are symmetric around the periods of the first and second modes of the Adriatic seiches, set to 21.8 and 10.7 h, respectively[17]. The reader is referred to Lionello et al.[14] and Ferrarin et al.[7] for a more detailed description of the aforementioned sea level decomposition analysis.

According to the sampling theorem, the minimum period resolved by the data is twice the sampling interval. Moreover, oscillations of smaller periods may be aliased to larger periods (e.g. an oscillation having a period of 5 h would appear as a false signal at a period of 30 h in 6-hourly time series). In other words, by using a sampling interval of 6 h we would be unable to document oscillations of periods smaller than 12 h and, furthermore, if such oscillations do exist in the original time series they would contaminate the signals having periods larger than 12 h. Therefore, due to the low sampling interval of the 1872–1939 dataset, the contribution of the high-frequency surge to the sea level (period < 10 h: MAV set-up, meteotsunami and high-frequency local surge) was computed only for the 1940–2019 timeseries.

In order to ensure serial independence among individual extreme events, the original time series was subsampled to obtain a homogeneous high and low waters time series for the whole 1872–2019 period (203,100 values, approximately two high and two low waters per day). The subset correctly represents the time evolution of the long-term relative sea-level rise, as well as the tidal and seiche extremes. Indeed, the Kolmogorov-Smirnov, Andreson-Darling and Mann-Whitney tests confirmed that for the storm surge, PAW surge and IDAS contributions, the distribution of the high-low subsample does not differ (with statistical significance, p-value \(> 0.05\)) from the one of the original datasets. The tests were not successful for the high-frequency oscillations, but the subsample contains the most significant events (considered as the ones with values higher than 0.15 m).

Extreme value analysis

The following analysis is based on the notion of Hazard Scenario as the upper set of the events above a given threshold[50], e.g. the ESL larger than some critical limit (see also the Supplementary Information). The probability \(\alpha\) of events belonging to a Hazard Scenario is typically small, so that they are characterized by return periods \

($RP = \mu /\alpha$) generally longer than μ, where μ is the average inter-arrival time between successive occurrences in the time series. Such an approach can be applied both for univariate and multivariate analyses. In our analysis, the Hazard Scenario is the set of events above a sea level threshold representing a high percentile of the overall distribution.

The multivariate analyses carried out in the present work are based on the mathematical Theory of Copulas[34,35]. A copula is a multi-dimensional function that models the statistical dependence (or independence) among a set of variables of interest, which in our case are the different contributions to the sea level anomalies. Copulas are used to provide the overall probability of a compound critical event accounting for both the marginal random behavior of the variables involved and their joint statistical interactions (e.g., when considering the ESL as the aggregation of several non-independent drivers).

The very first step in any multivariate analysis is to check the *degree of association* (viz., concordance or discordance) between pairs of variables (e.g. via the non-parametric Kendall's rank correlation τ). Should two variables be regarded as dependent, then a number of parametric copulas[34,35] could be used to model their dependence structures. Thanks to Sklar Representation Theorem[51], in order to construct a full statistical model of the random behaviour of the variables of interest, it is necessary and sufficient to individuate the marginal distribution functions of the single variables at play, as well as their copula(s). Several standard univariate distributions and different families of copulas have been used for the univariate and multivariate fits.

In this study, first a bivariate copula C_2 is fitted over the available pairs of (tide, NTR). Then, $M=10,000$ artificial independent samples of the vector (tide, NTR) are randomly generated from the fitted model. The analysis is then repeated but assuming that tide and NTR are completely independent, i.e., NTR maxima can occur at any phase of the tide. A set of $M=10,000$ artificial extreme sea levels is constructed aggregating tide and NTR (i.e., excluding the NLI). Furthermore, a 5-dimensional dependence model C_5 is fitted assuming that tide, seiche, storm surge, PAW surge and IDAS are all dependent. However, as for tide, seiche can also be considered as an independent factor contributing to the sea level. Therefore, we could consider the pair (tide, seiche) as independent of the triple (storm surge, PAW surge, IDAS). In turn, a 3-dimensional dependence model C_3 is fitted over the triple, and a full 5-dimensional copula $C^{'}_{5}$ is constructed as[35] $C^{'}_{5} (u_1, u_2, u_3, u_4, u_5) = u_1 \cdot u_2 \cdot C_3 (u_3, u_4, u_5)$, where $u_i \in [0, 1]$, with $i = 1,\ldots ,5$. This guarantees that the pair and the triple of variables considered are statistically independent. As above, $M=10,000$ artificial independent samples of the vector are randomly generated from the fitted models.

A more detailed description of the approach for the precise definitions of Hazard Scenario and Return Period is reported in the Supplementary Material.

Data availability

The sea-level data used in this study can be requested to the Centro Previsione e Segnalazione Maree - Protezione Civile, Venice, Italy, https://www.comune.venezia.it/it/content/centro-previsioni-e-segnalazioni-maree.

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Contributions

C.F. conceived the idea of the study, with the support of P.L. and M.O. C.F. and F.R. collected long-term data. G.S. and C.F. processed the data and analysed the results. G.S. conducted R processing. All authors discussed, reviewed and edited the manuscript.

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Ethics declarations

Competing interests

The authors declare no competing interests.

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14/05/2021

Abbraccio corvino - Veneto - Meteorologia - foto di Amelia De Lazzari

La parola chiave è adattamento. Su questo è centrato AdriaClim, progetto europeo con l'obiettivo di studiare gli effetti dei cambiamenti del clima sulle zone costiere dell'Adriatico e individuare le misure a vari livelli (comunale, regionale e nazionale) per ridurne l'impatto sulla società. Il progetto, coordinato da Arpa Emilia-Romagna, coinvolge Arpa Veneto e Arpa Friuli Venezia Giulia oltre a Ispra, università, istituti di ricerca e istituzioni pubbliche dell'Italia e della Croazia.

Il progetto europeo AdriaClim ha come scopo stimolare e promuovere politiche di adattamento in due modi:

- costruire una base conoscitiva all'avanguardia con le attuali conoscenze scientifiche, rendendola fruibile e accessibile ai decisori politici comunali, regionali e a ogni portatore di interesse della zona costiera dell'Adriatico;
- identificare e dare priorità, insieme a portatori di interesse locali (amministrazioni comunali, imprese, cittadini, ecc.), a una serie di misure per contrastare gli effetti dei cambiamenti climatici.

Il risultato sarà lo sviluppo di un sistema informativo utile a supportare le decisioni degli amministratori locali che saranno sempre più chiamati a fronteggiare gli effetti sul territorio dei cambiamenti climatici.

cambiamento climatico sulla fascia costiera dell'Adriatico e trasformare potenziali minacce in opportunità economiche.

Secondo il "*Piano Nazionale di Adattamento ai Cambiamenti Climatici* (Pnacc)", per il bacino del Mediterraneo entro il 2050 si prospetta il seguente scenario:

- la temperatura del mare Adriatico aumenterà di circa + 1.5 / 1.6 ° C
- il livello marino salirà di 7 cm, con possibile incremento dell'erosione costiera
- l'aumento di temperatura e volume del mare porterà a un incremento della salinità
- la salinizzazione dell'acqua dolce e degli acquiferi sarà sempre più frequente
- gli effetti avversi sull'ecosistema marino saranno inevitabili

Temperature più elevate associate a una maggiore frequenza ed entità delle mareggiate impongono sfide significative di gestione delle coste che possono essere affrontate al meglio se si mettono in atto gli sforzi combinati di istituzioni pubbliche, amministrazioni, enti di ricerca e portatori di interesse. Proprio in questo contesto si inserisce AdriaClim (*Climate change information, monitoring and management tools for adaptation strategies in Adriatic coastal areas*), concepito per contrastare gli effetti del cambiamento climatico sviluppando strategie di adattamento sulle aree costiere e marine adriatiche a rischio.

Il progetto, finanziato dal programma di cooperazione Interreg Italia-Croazia, è coordinato da Arpae Emilia-Romagna e coinvolge Ispra, Arpa Veneto e Arpa Friuli Venezia Giulia, oltre a università, istituti di ricerca e istituzioni pubbliche dell'Italia e della Croazia.

Obiettivi del progetto

L'obiettivo principale di AdriaClim è promuovere lo sviluppo di nuovi piani di adattamento regionali e locali e l'aggiornamento di quelli già esistenti per mitigare gli impatti del cambiamento climatico sulla fascia costiera dell'Adriatico e trasformare potenziali minacce in opportunità economiche.

Il progetto AdriaClim intende potenziare la cooperazione sui sistemi di monitoraggio, creando metodologie e protocolli transfrontalieri allo scopo di armonizzare gli strumenti e renderli accessibili a tutto il partenariato, e sviluppare modelli integrati ad alta risoluzione per migliorare la capacità di modellazione attraverso lo scambio di conoscenze ed esperienze tra Italia e Croazia.

Oltre a incrementare lo stato osservativo marino-costiero attraverso l'installazione di specifiche stazioni di misura, il progetto si propone di sviluppare una modellistica numerica accoppiata atmosfera-oceano-onde-fiumi a scala di bacino adriatico, con risoluzione di circa 5 km, e su aree pilota regionali a più alta risoluzione. Attraverso questa modellistica si riusciranno a ottenere indicatori locali più specifici e in questo modo gli amministratori e i decisori politici saranno in grado di comprendere i fenomeni a piccola scala indotti dai cambiamenti climatici e utilizzare le informazioni per sviluppare piani di adattamento regionali o locali.

Per rafforzare la capacità di adattamento e mitigazione in Italia e in Croazia, i piani regionali e locali saranno sviluppati in 9 aree test (6 italiane e 3 croate) dove i partner territoriali assumeranno la guida e coopereranno con le autorità locali e le parti interessate per aumentare la resilienza delle aree pilota coinvolte in questa attività.

Nell'ambito del progetto sarà inoltre istituito un Gruppo transnazionale di esperti nella Gestione delle tematiche del cambiamento climatico (*Transnational Expert Management Body*) con la funzione di organo di gestione transfrontaliero permanente, che favorirà la collaborazione tra le istituzioni italiane, croate e internazionali sui piani di adattamento e sulle misure di mitigazione.

Attività in Veneto

A rappresentare il sistema regionale Veneto sono ARPA Veneto, il Comune di Venezia, l'azienda sanitaria Aulss3 Serenissima, supportate scientificamente dalle Università di Cà Foscari e Iuav e dal Cnr di Venezia.

Arpav coordina il caso studio in Veneto. Due gli step operativi: la raccolta delle risultanze scientifiche, con il supporto dell'Università di Cà Foscari, e il loro trasferimento ai portatori di interesse attraverso incontri mirati sul territorio gestiti dal Comune di Venezia e Iuav.

Prodotti attesi dal progetto

Le azioni svolte da Arpa Veneto, in collaborazione con gli altri partner del progetto, mirano a ottenere i seguenti prodotti e attività:

- un geoportale, strumento dinamico con indicatori e informazioni relative agli effetti del cambiamento climatico sul territorio costiero Veneto, strutturato secondo le indicazioni individuate con i portatori di interesse comunali (amministrazioni comunali, attività economiche, ecc.);
- attività di informazione e condivisione sulle possibili azioni di adattamento ai cambiamenti climatici attraverso una serie di incontri con i portatori di interesse del territorio costiero Veneto, con particolare attenzione al comune di Venezia, ma anche agli altri comuni del litorale. I prodotti di supporto saranno linee guida e formazione sull'utilizzo del geoportale per la redazione di piani locali di adattamento ai cambiamenti climatici.

Esempio di prodotto: gli scenari climatici

Un'applicazione delle conoscenze attuali è rappresentata nel grafico. È riportata la variazione di temperatura media estiva ad Eraclea (Ve) misurata dalla stazione Arpav (linea rossa sottile spezzata dato annuale, linea rossa spessa andamento medio) e le proiezioni di modelli climatici per tre tipi di possibili realtà future: un futuro dove la società non ha cambiato la sua economia e modalità di sviluppo (**linea viola**), un futuro dove lo sviluppo della società è diventato molto rispettoso dell'ambiente (**linea verde**) ed uno scenario intermedio (**linea blu**).

Gli scenari climatici sono il risultato di una media di varie simulazioni climatiche effettuate da diversi gruppi di ricerca europei e messi a disposizione gratuitamente in rete (gruppo di lavoro Cordex). Il progetto Adriaclim parte da queste basi di conoscenza per sviluppare un sistema informativo di supporto ai decisori locali.

Attività in Friuli Venezia Giulia

Arpa FVG contribuisce al conseguimento degli obiettivi del progetto AdriaClim realizzando delle simulazioni numeriche, ad alta risoluzione spaziale, riguardanti le caratteristiche fisiche **del golfo di Trieste e della laguna di Grado e Marano,** che sono l'area pilota del progetto per Arpa FVG (Fig. 1). Tali simulazioni hanno lo scopo di valutare la sensitività dell'ambiente marino-costiero rispetto agli scenari di cambiamento climatico globale, generando una base inedita di dati, che saranno di supporto alla realizzazione di piani locali di adattamento al clima che cambia.

Al fine di trasferire efficacemente le informazioni scientifiche ai portatori di interesse, Arpa FVG sta inoltre coinvolgendo gli amministratori locali, e in generale la comunità che vive e opera nell'area costiera e lagunare della regione FVG, in un **processo informativo e partecipativo**, nel quale vengono identificati i potenziali impatti che i cambiamenti climatici produrranno sull'ambiente e sulle attività umane, nei prossimi decenni.

A tale proposito si segnala la prima serie di **4 incontri**, che si svolgeranno a **maggio e giugno 2021**, dal titolo **"Cambiamenti climatici e adattamento locale nelle aree costiere e lagunari del FVG",** un'iniziativa organizzata in collaborazione con APE FVG (Agenzia Per l'Energia del Friuli Venezia Giulia) e INFORMEST (Agenzia per lo Sviluppo e la Cooperazione Economica Internazionale), per fare sinergia con altri progetti aventi obiettivi che si intersecano con quelli di AdriaClim, in questo caso specifico il progetto RESPONSe.

>> ***Scarica l'invito*** *"Cambiamenti climatici e adattamento locale nelle aree costiere e lagunari del FVG"*

>> ***Scarica il programma*** *dettagliato del percorso informativo e partecipativo "Cambiamenti climatici e adattamento locale nelle aree costiere e lagunari del FVG" che avrà inizio giovedì 13 maggio 2021*

A proposito di effetti del cambiamento climatico…

A livello europeo e nazionale si stanno applicando diverse politiche per cambiare il modello economico e renderlo meno impattante sulla natura, sensibilizzando la popolazione a stili di vita più sostenibili dal punto di vista ambientale. Queste azioni, definite di mitigazione, richiederanno molto tempo e risorse per essere attuate e avranno effetti solo nel lungo periodo. Nel frattempo occorre far fronte ai cambiamenti climatici individuando azioni di adattamento anche attraverso progetti come AdriaClim.

Per maggiori informazioni e contatti su progetto AdriaClim:

- Pagina internet del **progetto Adriaclim**
- Scheda di progetto redatta ed aggiornata da **Arpae Emilia Romagna**
- Scheda di progetto redatta ed aggiornata da **Arpa Friuli Venezia Giulia**
- Scheda di progetto redatta ed aggiornata da **Arpa Veneto**

Leaflet del progetto

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Interreg Italy - Croatia AdriaClim

CHI SIAMO

Diciannove partner dall'Italia e dalla Croazia impegnati nella ricerca di soluzioni per contrastare gli effetti del cambiamento climatico sulle coste e sulle isole del mare Adriatico.

LEAD PARTNER

Arpae - Agenzia regionale per la prevenzione, l'ambiente e l'energia dell'Emilia-Romagna

PARTNER DEL PROGETTO

CNR-ISMAR (IT) / ARPA Veneto (IT) / Agenzia per lo Sviluppo della provincia di Zadar ZADRA NOVA (HR) / Provincia di Dubrovnik Neretva (HR) / Istituto Ruder Boskovic (HR) / RERA Split – Provincia della Dalmazia (HR) / Istituto di Oceanografia e Pesca (HR) / Regione Puglia (IT) / Fondazione CMCC (IT) / Università di Bologna (IT) / ARPA FVG (IT) / ISPRA (IT) / Regione Marche (IT) / ULSS3 Serenissima (IT) / Regione Molise (IT) / Regione Emilia-Romagna (IT) / Città di Venezia (IT) / Regione dell'Istria (HR)

AdriaClim è finanziato dal programma Interreg Italia-Croazia.

Interreg è uno degli strumenti chiave dell'Unione Europea (UE) che promuove la cooperazione transfrontaliera tra Italia e Croazia finanziando progetti mirati alla risoluzione di problemi attraverso lo scambio di conoscenze ed esperienze in tutti i settori e migliorando la qualità della vita di più di 12.4 milioni di abitanti.

Fondo Europeo di Sviluppo Regionale

PARTNER DEL PROGETTO

CONTATTI

Agenzia regionale per la prevenzione, l'ambiente e l'energia dell'Emilia-Romagna (Arpae)

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Scopri di più su AdriaClim
www.italy-croatia.eu/adriaclim

Interreg Italy - Croatia AdriaClim

AdriaClim

Informazioni, monitoraggio e strumenti di gestione per le strategie di adattamento al cambiamento climatico nelle aree costiere dell'Adriatico

Proteggi la costa, adattati al cambiamento climatico!

Fondo Europeo di Sviluppo Regionale

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Research Article

Saltwater Intrusion in a Mediterranean Delta Under a Changing Climate

Debora Bellafiore, Christian Ferrarin, Francesco Maicu, Giorgia Manfè, Giuliano Lorenzetti, Georg Umgiesser, Luca Zaggia, Arnoldo Valle Levinson,

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Abstract

Saltwater intrusion (SWI) in deltas, estuaries, and other coastal areas represents a pressing problem affecting the sustainability of freshwater resources. Observations and numerical experiments are used to investigate SWI in the surface waters of the Italian's largest river delta (the Po Delta) under low discharge conditions. The model successfully reproduced the observed salinity variations along main river branches and in the delta lagoons and investigated fresh and saltwater dynamics during the entire summer 2017. The numerical model is used to explore the hydrological response of the delta system to climate change. The relative effect of controlling factors on saltwater penetration, such as sea-level rise (SLR), air-sea fluxes, and reduction of river discharge, was evaluated. Results suggest that changes driven by climate and SLR will exacerbate SWI in the surface waters of the Po Delta system. Extent of SWI in the major river branch is projected to increase up to 80% further into the river. Persistence of SWI at the same site is expected to increase 100% longer. Moreover, additional synthetic simulations were used to investigate the sensitivity of SWI to several river discharges and relative SLR values, highlighting the effects of the two factors in the delta. Such results show different combinations of river discharge and relative SLR values that represent possible scenarios, and are important for managing SWI in river-sea systems affected by both climatic and anthropogenic factors such as discharge changes from dam construction, land use, and irrigation.

Open Research

Data Availability Statement

Modeled 3D maximum salinity for the present day condition (summer 2017) and the RCP8.5 scenario are available in Zenodo (Bellafiore et al., 2020). The open source model SHYFEM (Umgiesser et al., 2018) is freely available on the web pages http://www.ismar.cnr.it/shyfem and https://github . com/SHYFEM-model (https://doi.org/10.5281/zenodo.1311736). CTD profiles acquired in the field campaign on the 26th of July 2017 and used for validation are available in Zenodo (DOI 10.5281/zenodo.4045663).

Citing Literature

Supporting Information

Filename	Description
2020JC016437-sup-0001-Figure SI-S01.pdf 260.6 KB	Figure S1

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